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Capture-ready supercritical coal-fired power plants and flexible post-combustion CO₂ capture

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Abstract

Delivering a rapid reduction in global CO₂ emissions through CCS requires a two-track approach: CCS needs to be developed at scale as quickly as possible and other plants, if built without CCS, need to be built CO₂ capture ready (CCR). CCR plants can be upgraded as CCS technology develops so that their cost of electricity production can be minimised. Retrofitted CCR plants could also be very suitable for providing flexible electricity output. The options available for making steam turbines at pulverised coal plants suitable for adding post-combustion CO₂ capture units are discussed, together with their potential for upgrading and enhanced flexibility.

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1. Introduction

As long as fossil fuels are being used Carbon Capture and Storage (CCS) technologies will be required to limit anthropogenic carbon dioxide (CO₂) emissions to the atmosphere to acceptable levels. CCS could be particularly important for coal since reserves are still abundant [1] and a large part of electricity generation worldwide currently relies upon it. Post-combustion CO₂ capture is one approach that is expected to be used in global roll-out of CCS [2]. One of its principal advantages is its great potential for flexibility in design and operation. For example, this facilitates the design of capture-ready pulverised coal plants. The concept of capture-readiness represents an appropriate answer to the large coal-based generation capacity that is being built in developing countries such as India and China. Anecdotal evidence suggests that these countries are not likely to take significant action to mitigate their CO₂ emissions before credible action is seen in developed countries. A global strategy of cutting global emissions by around 50% by mid-century has been suggested as an appropriate response to current understanding of potential global temperature rises that are likely for different stocks of CO₂ in the atmosphere. It is likely that this

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target will be difficult or impossible to meet unless it is possible to retrofit CCS to the vast majority (and preferably all) coal plants that will be built in the next two decades. This paper will, therefore, first explore how post-combustion capture can facilitate the concept of capture-ready plants at limited additional cost.

A common requirement for capture systems using current amine solvents is the significant amount of heat at 110–120°C required for solvent regeneration. This heat is most efficiently provided by condensing steam extracted from the power cycle and the best location to extract such a large amount of steam is the crossover pipe between the Intermediate Pressure (IP) and Low Pressure (LP) turbines [3], where the pressure must be controlled to make steam available that will condense at the required temperature. Extracting steam from the power cycle obviously results in a reduced LP turbine output and a reduced condenser mass flow. Waste heat from the capture process can be recovered for feed water heating in the power cycle, but the amount of low-grade heat available is significant and only a fraction can be used. The rest of it has to be rejected through the cooling system of the retrofitted plant. But improved solvent regeneration approaches that use less energy and that make better use of process waste heat can be expected to be developed, combined with better solvents with reduced energy requirements. It is obviously impossible to predict future solvent developments, perhaps 10 or 20 years ahead. Steam flows are, however, expected to be lower in the future so it can be said that capture-ready steam turbines may be required to operate with steam extraction rates that vary from relatively high values with current solvents down to even as low as zero to accommodate future capture systems.

Extraction pressures are more difficult to predict as they relate to the temperature of regeneration of the solvent. They may well remain constant since amine solvents, e.g. aqueous monoethanolamine (MEA), will probably remain attractive for some time and regeneration at pressure slightly above atmospheric will continue to require heat at about 120°C, even if in smaller amounts. Alternative amine solvents such as aqueous piperazine [4, 5] degrade, however, at higher temperatures – around 150°C – which for optimum process efficiency, through CO₂ liberation at as high a pressure as possible, will require an elevated pressure for the steam supply compared to current MEA-based design. Alternatively, other promising solvents such as sterically hindered amines or potassium carbonate-based solvents have a temperature of regeneration below the ~120°C requirement for typical MEA-based solvents [3, 6, 7]. This sets a difficult challenge for plant developers and, more specifically, steam turbine manufacturers attempting to predict the pressure required for future steam supply. But the intrinsic flexibility of both aqueous solvents capture systems and steam turbines means that ‘lock in’ to a particular technology is not necessary. Plant operators should be able to upgrade their plant as new solvents come into the market, helping them to maintain competitive marginal costs of electricity. This will be examined in the second part of this paper (Section 3).

When ‘capture-ready’ (and existing non-CCR) plants are retrofitted with post-combustion capture the capacity of the generator remains unchanged. If steam extraction rates can be temporarily reduced (possibly to zero) by intentionally bypassing the post-combustion capture system or by using previously-stored solvent, the gross power output of the turbines can be returned to their pre-retrofit value. If CO₂ is recycled in the compression train and the solvent regeneration system is kept warm, but with significantly reduced flows, then this increased power output could be made available while also retaining the potential for a rapid shift back to ‘standard’ capture operation, or any intermediate output, with a suitable plant configuration and control system. This capacity brings additional flexibility into the electricity network at no additional costs for the system operator so could make these plants a valuable asset. It is therefore important that policy-makers understand the pros and cons of various approaches to flexible operation of power plants with CO₂ capture when developing legislation. The last part of this paper (Section 4) will investigate what levels of flexibility can be achieved for pulverised coal plants with aqueous solvent-based post-combustion capture.

2. Capture-ready pulverized coal plants: steam turbine options

Capture-ready gives an option to plant developers to fit capture in the future to protect the value of their investment against potential future increases in CO₂ emission pricing or a regulatory requirement for CCS. A capture-ready plant fleet should also enable a country to make more rapid and less costly CO₂ emission reductions in the future, as well as demonstrating the commitment of a company or a government towards CCS. In this paper, we will follow the International Energy Agency Greenhouse Gas R&D Programme (IEA GHG) recommendation that for a plant to be capture-ready a number of essential requirements must be fulfilled [8] The consensus is that only

minimal up-front capital costs and minimal reduction in efficiency can be justified, or are required, given that the economics depends critically on unknown parameters such as time to fit capture, future fuel, CO₂ prices etc [9, 10]. Therefore only inexpensive options with little or no effect on plant performance prior to retrofit have been considered. These are:

- Locate the plant close to a CO₂ storage site;
- Identify a route for CO₂ transport either by ship or pipeline;
- Leave space adjacent to the site for capture equipment to be fitted and built, including access in critical locations for connections to be made; and
- Ensure the feasibility of a retrofit with a feasibility study.

Plant developers should also consider making the plant ‘retrofit-friendly’ so that the power plant can be operated during the majority of the construction programme required for the CO₂ capture retrofit. A plant outage to make final connections will be required, but if this can be kept as short as possible (and preferably integrated with a planned outage that would be required anyway) then significant lost revenues associated with requiring a plant shutdown can be minimised. With regards to amine-based systems technology specific requirements are:

- Consider potential changes to FGD (flue gas desulphurisation) equipment design so that high levels of SO_x removal can be achieved, when required, although some developers may prefer to add a polishing unit after a previously installed FGD process during the CO₂ capture retrofit; and
- Make the steam cycle ‘capture friendly’ so as to be able to supply any steam required for thermal regeneration of the capture solvent with the minimum loss of plant performance both before and with CO₂ capture.

Pulverised coal plants retrofitted with post-combustion capture are capable of being fully integrated both before CO₂ capture and with CO₂ capture. Since it is expected that many pulverised coal power stations will be built before CCS is commercially viable it has been proposed that they are built ‘capture-ready’ to ensure that a retrofit is possible. Plants can be retrofitted to protect against consequent carbon emission lock-in, as noted above, while ensuring that the effective price of CO₂ expected to be included in the cost of electricity can be capped at the cost of capture in the future. At the same time, effective thermodynamic integration of the post-combustion capture equipment with the power cycle ensures good performance with minimal impact on lifetime plant economics.

In this paper, we present a detailed consideration of steam turbine and associated power cycle design for three capture-ready plant options, all with supercritical steam conditions (290bar/600°C/620°C) and capable of good thermodynamic integration, low cost and minimal need for modifications through. A model of the power cycle was developed [11] based on a study by Alstom, Mitsui Babcock (now Doosan Babcock), Fluor and Imperial College [12]. The results of the model both without and with capture are consistent with the steam cycle model used by Alstom while the energy requirements for solvent regeneration are based on the Fluor’s Econamine FG CO₂ capture technology, which uses a mono-ethanolamine (MEA) based solvent. The original fixed design point system analysis was improved to take steam turbine retrofit into account for steam extraction for the post-combustion capture unit and then developed to include part-load performance of retrofitted plants at variable levels of CO₂ capture. Key features of the three configurations are illustrated in Figure 1.

Clutched LP Turbine: Option 1

This option is the most efficient, but also the least flexible and the most expensive, as it requires extensive modification of the turbine hall compared to a non capture-ready design. The clutch between the two turbines will add cost and complexity, with no immediate benefit when the plant is operated before a retrofit. The clutched LP turbine cylinder will be taken out of service for capture operation without affecting the steam cycle temperatures and pressures. The IP/LP crossover pressure would be set at the desired value for solvent regeneration. The remaining LP turbine cylinder still operates at its design conditions after capture is retrofitted, avoiding any additional losses.

Throttled LP Turbine Retrofit: Option 2

The crossover pressure remains constant in this option too due to a throttling valve downstream of the steam extraction point. Significant throttling losses occur when operating with capture, however, and this option is the least efficient of the three. Up-front capital costs are minimal though, with the principle additional items being a flange for a suitably-sized steam offtake to be connected at the IP/LP crossover and a spool piece for the throttling valve.

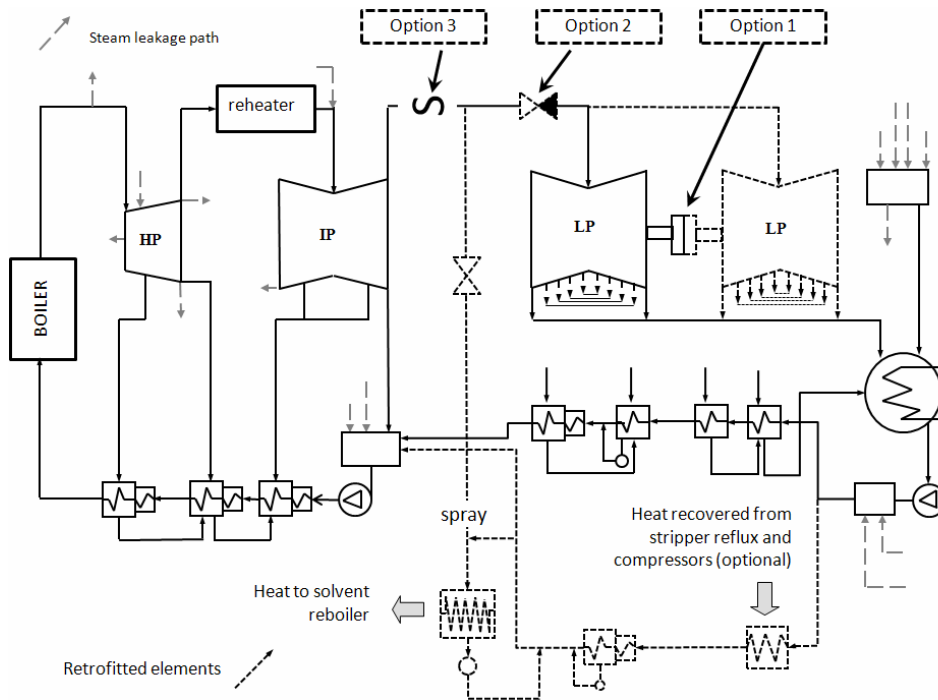


Figure 1: Capture-ready steam turbine layouts

Option 1: Clutched LP turbine

- Most efficient design.
- Both the steam extraction flow rate and the steam extraction pressure cannot vary.

Option 2: Throttled LP turbine

- Simplest design but losses in throttling valve.
- The steam extraction flow rate can vary.
- The steam extraction pressure cannot vary.

Option 3: Floating IP/LP crossover pressure

- No throttling losses when retrofitted.
- Small turbine efficiency penalty.
- The steam extraction pressure increases with reduced steam extraction rate.

Floating IP/LP crossover pressure: Option 3

In this option the pressure at the IP/LP crossover pipe is originally higher than in the two other options. When the capture unit is connected the pressure falls to the value that is required for operation with the MEA-based capture unit. The turbines suffer a small efficiency penalty since they are operating away from their original design point, although this is likely to be within acceptable variations. There are no throttling losses and the performance is intermediate between the two other options. The last stage blades of the IP turbine and the first stage blades of the LP turbine need to be reinforced because of increased stage loadings, i.e. axial thrust changes, increased blade bending moment and possible flow restrictions. A flange for a suitably-sized steam offtake and spool piece for an optional throttling valve will also be required. But additional costs for these modifications are expected to be relatively low.

Table 1 summarises power loss and capital costs for additional pre-investments for capture-readiness. Total capital requirements are reported in [8]. It should also be noted that combinations of these turbine options are possible, depending on the strategy adopted by a given plant developer. For example, a hybrid system having one clutched LP turbine cylinder out of three and a throttling valve at the inlet of the two remaining cylinders would give some flexibility and an intermediate performance penalty. Another hybrid system could be a throttling valve in addition to some variation of the IP/LP crossover pressure to confer benefits achievable with each configuration (i.e. improved flexibility/response times and reduced losses respectively).

Table 1: Comparison of the power loss of capture-ready options

	New plant w/o CCS	New plant with CCS	Clutched LP turbine	Throttled LP turbine	Floating pressure
Efficiency w/o CCS (%LHV)	45.5		45.5	45.5	45.5
Efficiency w. CCS (% LHV)		36	35.1	35.7	36
Additional capital [8]			2.89	0.41	0.74

3. Potential for solvent upgrade

Capture-ready steam turbines will be designed for a given steam extraction rate at the IP/LP crossover pipe to provide the right amount of heat for a specific solvent. Although it is impossible to design a capture-ready steam cycle with an ideal efficiency for a range of solvents, it is feasible to design steam cycles that achieve performance close to the ideal for a given range of solvents. Future performance of solvents remains, by definition, unknown but reasonable options in the design of the steam cycle can handle a wide range of uncertainty. The model used in this study was extended to take a range of steam flow rates into account. The example chosen was a MEA-based system that was upgraded with another amine solvent with a lower energy requirement but a similar temperature of regeneration, e.g. an upgrade from 30 wt% MEA to a blend of MEA and MDEA [13]. The reaction rate of absorption of MDEA is slower than MEA. Additional packing height in the original absorber system would be required for optimal conditions to cope with slower kinetics in the column or an additional absorber column could be connected in series (or parallel) with the original absorber system. The performance of the throttled LP turbine option and the floating pressure option for a range of solvents with different energy requirement is compared with the performance of a range of new-build CCS units specifically designed for the extraction rate of the upgraded solvent. The clutched LP turbine was not considered as it offers very little flexibility for upgrade since the additional LP steam flow available cannot be handled by the remaining turbine cylinder. Additionally, we investigated the performance of a hybrid system with a throttling valve at the inlet of the LP turbine and a floating IP/LP crossover pressure designed for a solvent requiring 20% less energy for regeneration. The results are presented Figure 2. These results incorporate a constant ancillary power for the power plant, since there is no change in boiler load and therefore no change in the amount of CO₂ generated with a constant CO₂ capture level. It was also assumed that there was always enough waste heat available in the capture unit to be recovered in the power cycle.

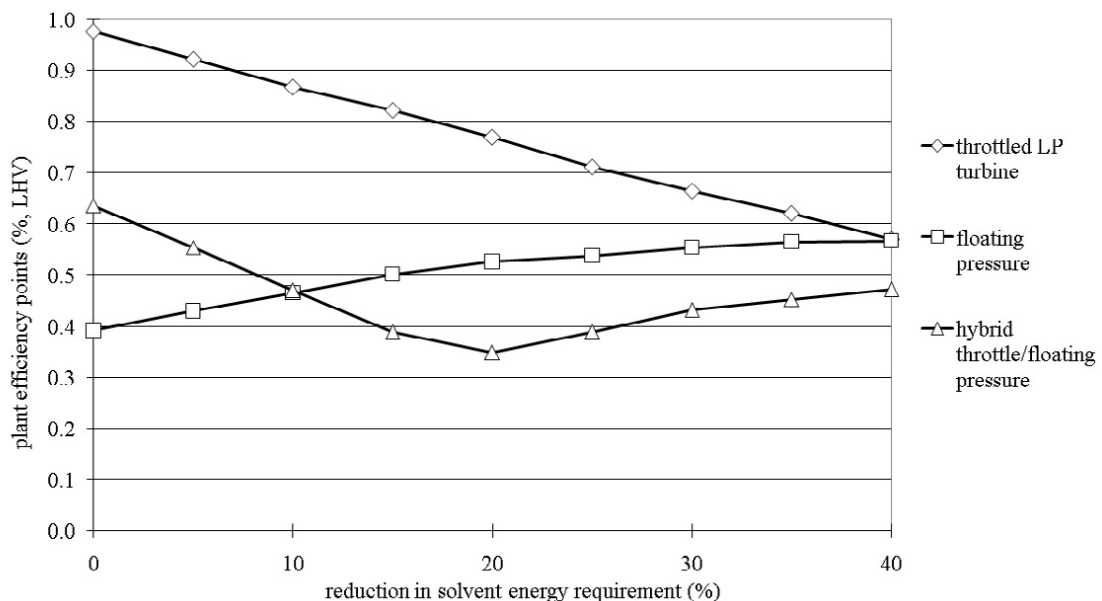


Figure 2: Efficiency penalty for a range of new solvents compared to a new-build plant designed for that specific solvent (note the original solvent case is on the LH side of the graph, at zero reduction in energy requirement) [11]

Throttled LP turbine retrofit: The temperature for solvent regeneration in the capture unit is limited to the design value or lower since the IP/LP crossover pressure cannot be increased. Throttling losses at the LP turbine inlet are reduced as more steam is available to the turbines, so the difference from the ideal plant performance for a specific solvent decreased with reduced solvent energy requirements.

Floating pressure retrofit: The pressure at the IP/LP crossover increases with reduced steam extraction rate. For this specific solvent upgrade the same regeneration temperature is assumed as for the original design solvent. The extracted steam therefore needs to be throttled and desuperheated to control temperature in the reboiler to protect the

solvent from thermal degradation. Elevated steam pressure does, however, give the option to increase the temperature of regeneration, with the increased CO₂ delivery pressure likely to be advantageous, if a new solvent can withstand the conditions with acceptable degradation rates. This increase in the temperature of regeneration is not possible with the throttled LP turbine design.

Throttled/floating pressure hybrid retrofit: In this option, throttling losses upstream of the LP turbine gradually reduce to zero for a 20% reduction in extraction rate. Further reduction leads to an increase in pressure at the IP turbine outlet so a throttle then has to be used in the steam extraction line for this case.

The hybrid system offers a good compromise between the other two options. The plant is respectively 0.2 percentage points less efficient and 0.35 percentage points more efficient than the floating pressure and the throttled LP when operated with the original 30 wt% MEA solvent. Any upgrade with a new solvent with more than a 10% reduction in its regeneration energy requirements makes the hybrid option the most option efficient of the capture-ready options discussed in this paper. For solvents like aqueous potassium carbonate that can be regenerated at a lower temperature than MEA, around 55°C–60°C, the specific heat to bring the solvent from the absorber temperature to the temperature in the reboiler/regenerator is greatly reduced and so is the energy of regeneration. A lower temperature in the regenerator is attained through a lower steam pressure. A valve in the extraction line would then be required to reduce the pressure of the steam and the losses generated may offset any gain in energy of regeneration. It is, therefore, likely that ‘upgrading’ a capture-ready unit based on MEA with a low temperature solvent may not be advantageous. A full LP turbine retrofit might be needed to provide steam at the required pressure with associated capital cost requirements.

A clutched LP turbine configuration would give plant developers the best performance for a given solvent but first movers into the technology could face higher operational costs due to sub-optimal design as new solvents came onto the market. In contrast, throttled LP and floating pressure configurations that can benefit from improved solvents should allow them to maintain a more competitive marginal cost of electricity compared to ‘late-movers’ so that they remain well-placed in the plant-dispatch merit order (which effectively determines which plants are likely to generate power (and hence make profits) within the electricity system at any particular time).

4. Increased flexibility with post-combustion capture

Capture-ready steam turbines can cope with steam extraction rates temporarily reduced to zero (although with a slower response time for the clutched LP design) while the waste heat recovery exchanger can be by-passed easily and operations returned to using ‘normal’ feed water heating from the LP turbine (provided that heaters have been retained). Reduction of steam supply to the capture unit will reduce CO₂ capture levels in the order of a few minutes as the temperature of the aqueous solvent decreases. The thermal inertia of the aqueous solvents will allow a rapid return to 90% capture level or more, however, after reasonable periods provided that the interruption (or almost complete interruption) of steam supply to the solvent reboiler/regenerator is matched by a corresponding reduction in the solvent recirculation rate.

State-of-the-art supercritical plants are capable of ramp rates in the region of 4% output/min over the entire range of the boiler load [14]. Rapid variations of LP turbine output through closure of the valve in the extraction line and opening the throttling valve upstream of the LP turbine could increase plant output – based on full-load operation with CCS – by approximately 17% within a few minutes. The additional steam available is sent to the LP turbine. Ancillary power for solvent pumps, fans and the compression train could also be avoided within minutes, adding another 8% to the output, allowing the plant to return to its pre-retrofit output for a given boiler load (i.e. the increase can occur without any additional fuel being fired). This makes the need for additional capacity due to the power output loss when CCS is retrofitted less crucial for electricity network operators since it can be recovered if required during periods of very high demand.

It should be noted that this could be done at full boiler but also at any boiler load between minimum stable generation and full output and while the boiler load itself is changing. Indeed, many future coal plants seem likely to operate at part-load for extended periods due to the increasing proportion of intermittent renewable power (e.g. wind). In systems with high penetrations of intermittent renewables (particularly if this is combined with some nuclear baseload plants) fossil plants will be required to operate at varying loads throughout the day to help balance

supply and demand. In these circumstances coal plants with improved ramp rates using flexible operation of the capture plant should be able to provide similar services to peaking plants.

Any intentional by-pass of the capture system would increase emissions, but this could be avoided if ‘lean’ solvent from a storage tank was kept flowing down the absorber to capture CO₂ and then was stored at the absorber outlet. The CO₂-rich solvent could be regenerated later, e.g. at night when demand and electricity selling price is low, when the plant may be required to operate at part-load anyway and the post-combustion capture unit is, therefore, operated at reduced levels [15]. One limiting factor for additional regeneration rate is the minimum steam flow required at the LP turbine inlet to ensure adequate blade cooling (typically 10% of normal design flow rate). An initial analysis of the potential economic value of this additional flexibility using solvent storage is available in [15, 16]. It should also be noted that different retrofit options are expected to have different flexibility performance:

Clutched LP turbine retrofit: A rapid by-pass of the capture unit in case of an outage or a partial reduction in the level of CO₂ capture is not possible with this option.

Throttled LP turbine retrofit: Rapid changes in power output can be achieved through quick variation of the steam extraction rate by modulating the opening of the valve in the extraction line and the valve at the LP turbine inlet. The plant could continue to operate if an unexpected outage of the capture unit occurred (depending on environmental permit conditions, or other legislation, which may limit allowable CO₂ emissions).

Floating pressure retrofit: Same order of flexibility is possible as with the throttled LP retrofit. The possible operating range for throttled LP unit has been modelled in [17] and is shown in Figure 3.

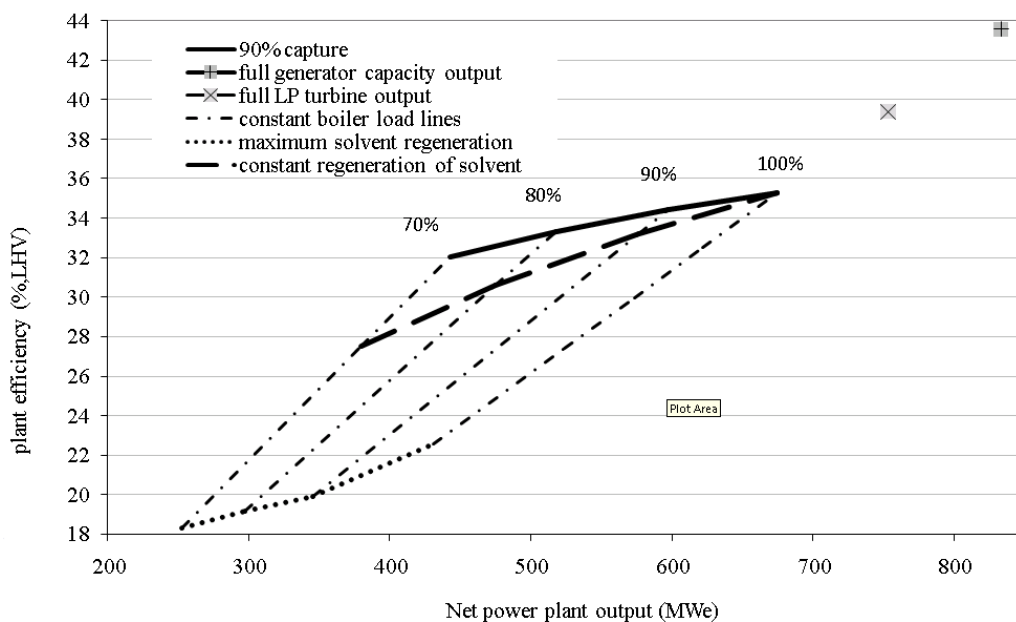


Figure 3: Range of operating patterns of a flexible LP throttled plant including - solvent storage at full boiler load with and without a shutdown of compression train and ancillary power and - additional solvent regeneration at constant boiler load

5. Conclusion s

Pulverised-coal plants can be made ‘capture-ready’ for post-combustion capture at low cost (less than 1% of total capital costs) using a throttled LP or floating pressure retrofit strategy. Both of these options, or a hybrid mixture of the two, have significant potential to perform well for a wide range of solvent energy requirements. Hence, they are able to cope with the inevitable uncertainties with respect to future capture system developments while benefiting from increased levels of flexibility of operation. A small penalty in efficiency (in the range of 0.5-1 percentage points compared to new build CCS plant) is, however, observed after retrofit compared to a new build CCS plant that also uses the solvent that the capture-ready plant was designed for. It is possible to achieve identical

performance for known technology both before and after retrofit with a clutched turbine retrofit approach but this approach requires significantly higher up-front costs and it would be impossible for operators to take advantage of many likely improvements with future solvents with this retrofit strategy. When capture-ready plants are retrofitted with post-combustion capture using a throttled LP or floating pressure approach, system CO₂ capture levels can be reduced down to zero to generate additional power, if required. This brings additional flexibility into the electricity grid with no additional capital expenditure so could avoid the need to construct additional capacity to compensate for lost power output when a CCS retrofit occurs. Solvent storage could also be considered; although additional capital expenditure would be required it would introduce many of the benefits associated with bypassing the CO₂ capture unit, but without increasing CO₂ emissions.

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